CPV in D→hh and D→Kππ at CDF

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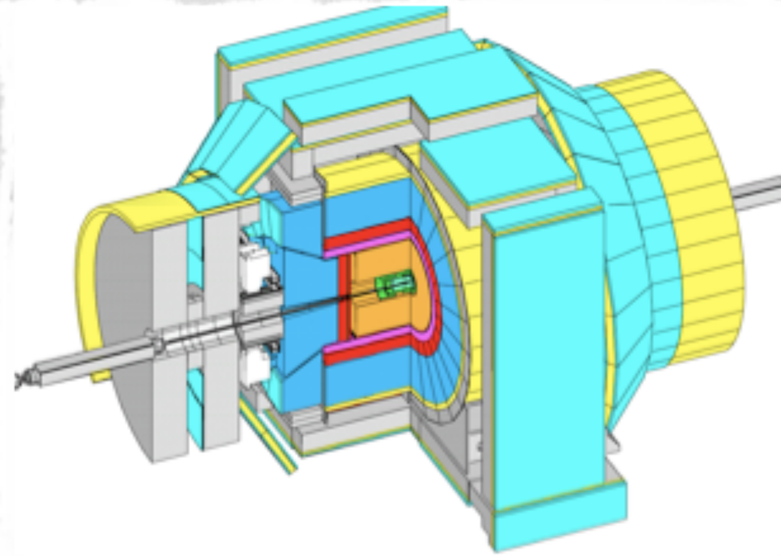
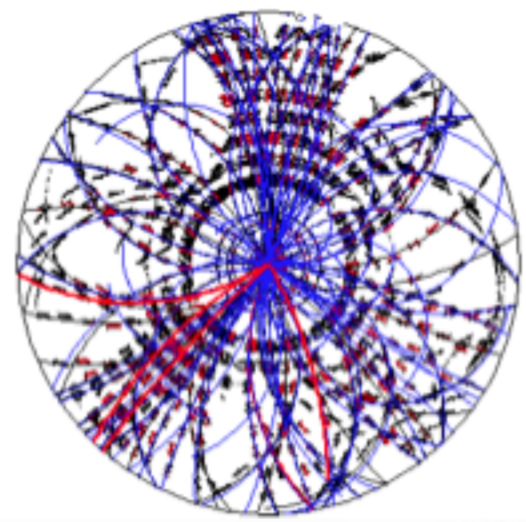
Honolulu, May 14-17, 2012

CDF and Charm

- CDF is a detector designed for top and Higgs that also does charm.
- 1% of collisions yield a D meson
- Reconstruct only charged decay products.
- Good momentum and decay-time resolution
- Some PID (not in these analyses)
- Trigger + offline efficiency 0.1-10%.





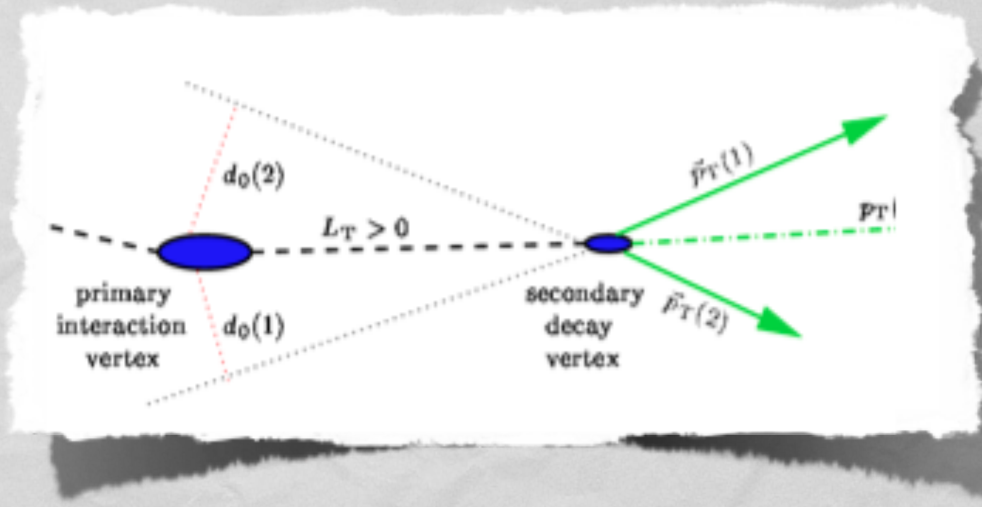
On-line selection by impact parameter Trigger

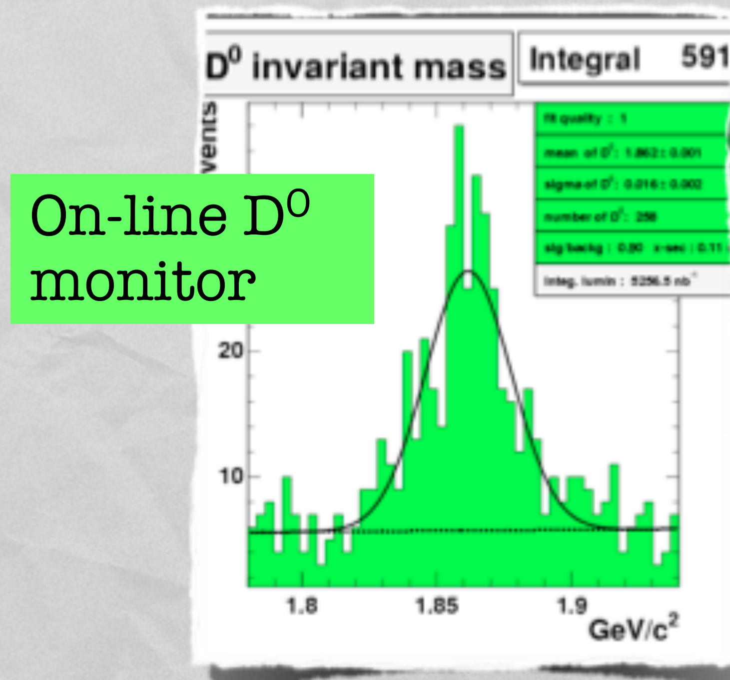
•Dedicated hardware: SVT (Silicon Vertex Trigger)

•In spite of the name, combines information from both silicon **and** drift chamber - Full tracking in < 20 μs

•Online selection: requires 2 tracks with pT > 2 GeV/c and i.p. >100μm - same as the main trigger for most of our B's. (Actually a quality monitor for the B trigger)

•Crucial role in D->hh analysis: boosts yields by factors x**10^4**



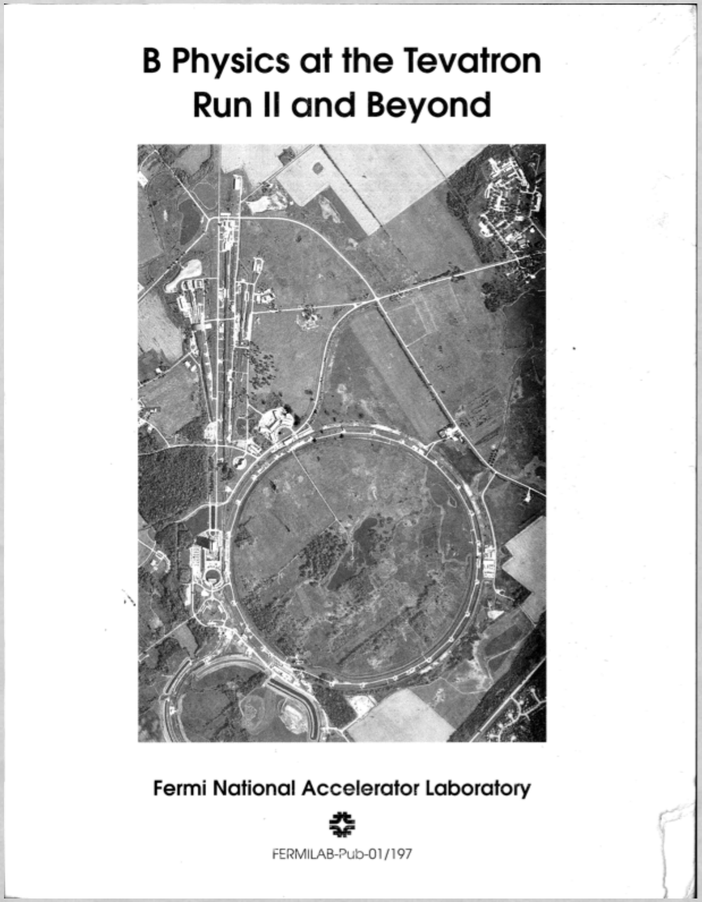


The unexpected Charm Decay Factory

• Fun fact: the 2002 planning document for HF program at Tevatron contains no reference to charm in ~600 pages.

•Then, the very first RUNII paper was about charm… and a few others followed.

- Ds+-D+ mass difference PRD68, 072004 (2003) 15 cit.
- Charm x-section PRL 91 241804 (2003) 139 cit.
- D->μμ PRD 68 091101 (2003) 31 cit. and PRD 82 091105 (2010) 5 cit.
- D->hh Br and CPV PRL 94, 122001 (2005) 55 cit. PRD 85, 012009 (2012) 20 cit.
- Excited D masses PRD 73 051104 (2006) 15 cit.
- D->Kπ WS analysis, PRD 74, 031109 (2005) 25 cit
- D mixing, PRL 100 121802 (2008) 111 cit.
- Charm baryons, PRD 84, 012003 (2011), 6 cit.



$D^0 \to \pi^+\pi^-$ and K^+K^-

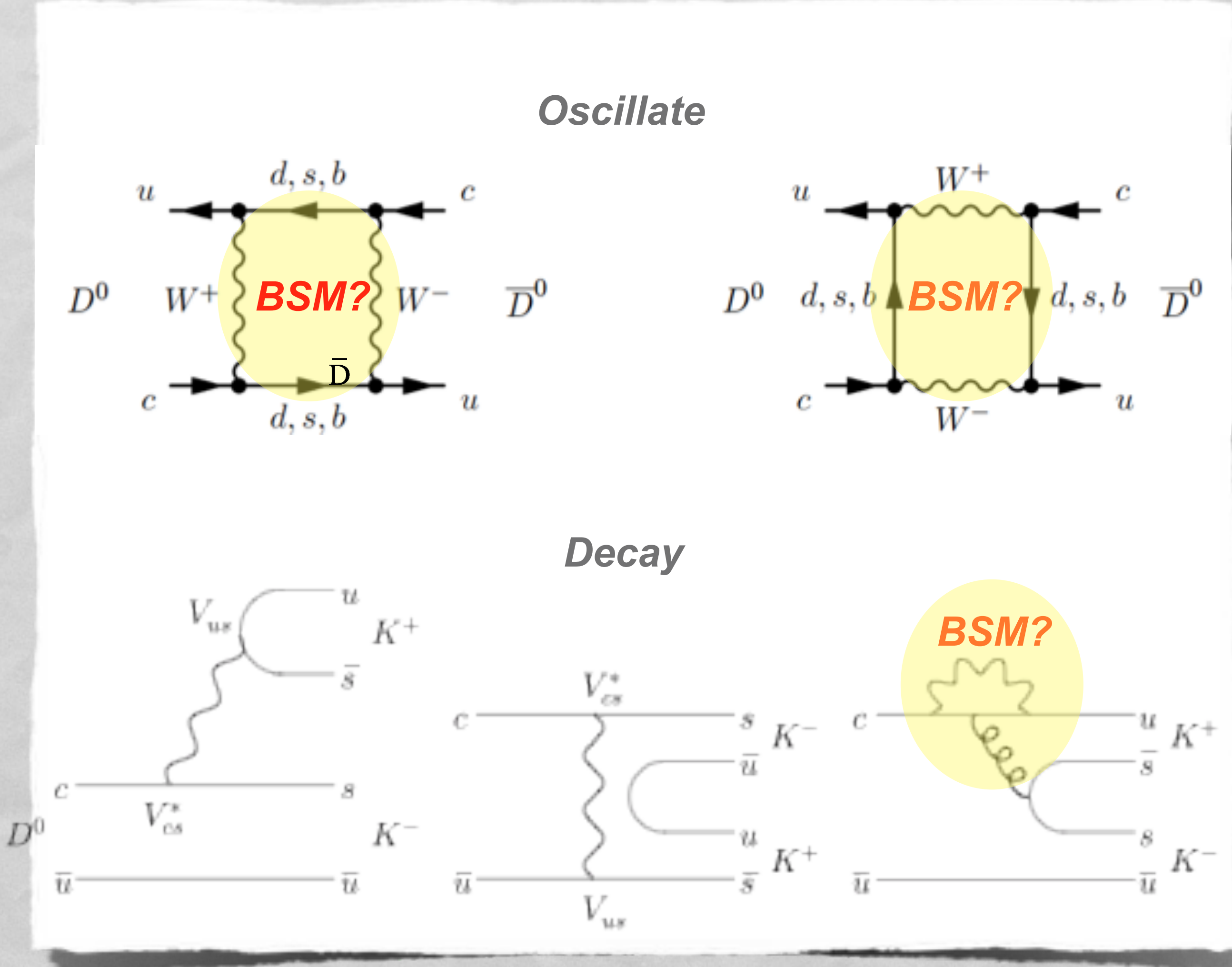
Both D^0 and $\bar{D}^0$ can decay into ππ or KK

Single-Cabibbo-Suppressed decays

"Tree" and "penguin" contributions make CPV observable

D^0 can also oscillate before decaying (box-diagrams)

Long-standing candidate for BSM effects to show up



Asymmetry measurement

$$A_{\rm CP}(D^0 \to h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\overline{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\overline{D}^0 \to h^+h^-)}.$$

- Asymmetry is time-dependent due to oscillations

- Here we present time-integrated measurements only

$$A_{\rm CP} = a_{\rm CP}^{\rm dir} + \int_0^\infty A_{\rm CP}(t)D(t)dt \approx a_{\rm CP}^{\rm dir} + \frac{\langle t \rangle}{\tau} a_{\rm CP}^{\rm ind}.$$

- Indirect a_{CP} is independent of decay mode

- Infer initial D flavor by requiring it to come from a charged D* decay.

$D^{*+} \to D^0\pi^+ \to [\,h+h-\,]\,\pi^+$

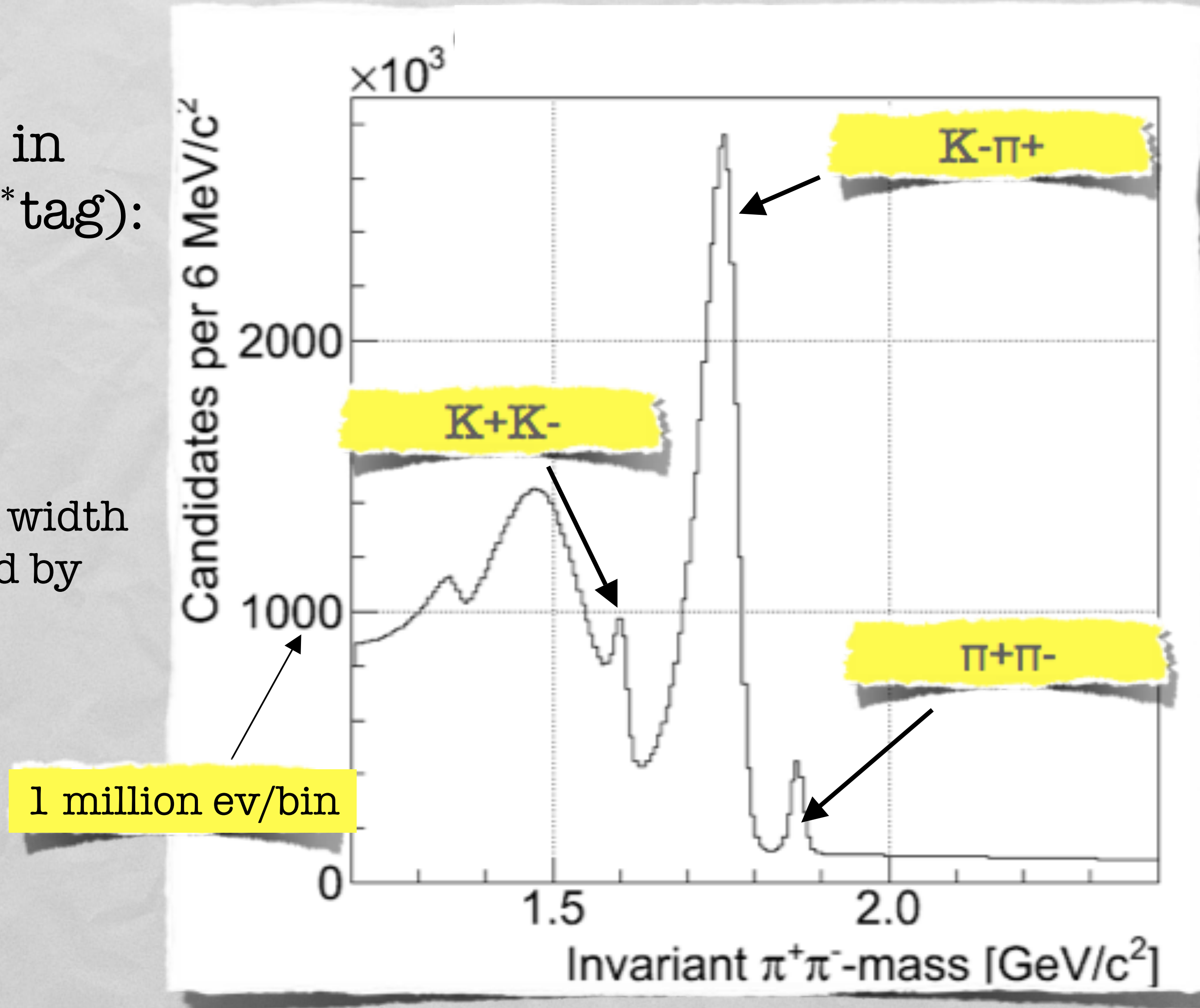
$D^{*-} \to \overline{D}^0\pi^- \to [\,h+h-\,]\,\pi^-$

Strong D* decay conserves charm flavor, correlated with the pion charge

$D^0 \to h^+h'^-$ signals @CDF

- Total samples in $10fb^{-1}$(after D^*tag):
  - 1.21M KK
  - 0.55M ππ

(N.B.: in this plot Kπ width artificially inflated by nominal ππ mass assignment)



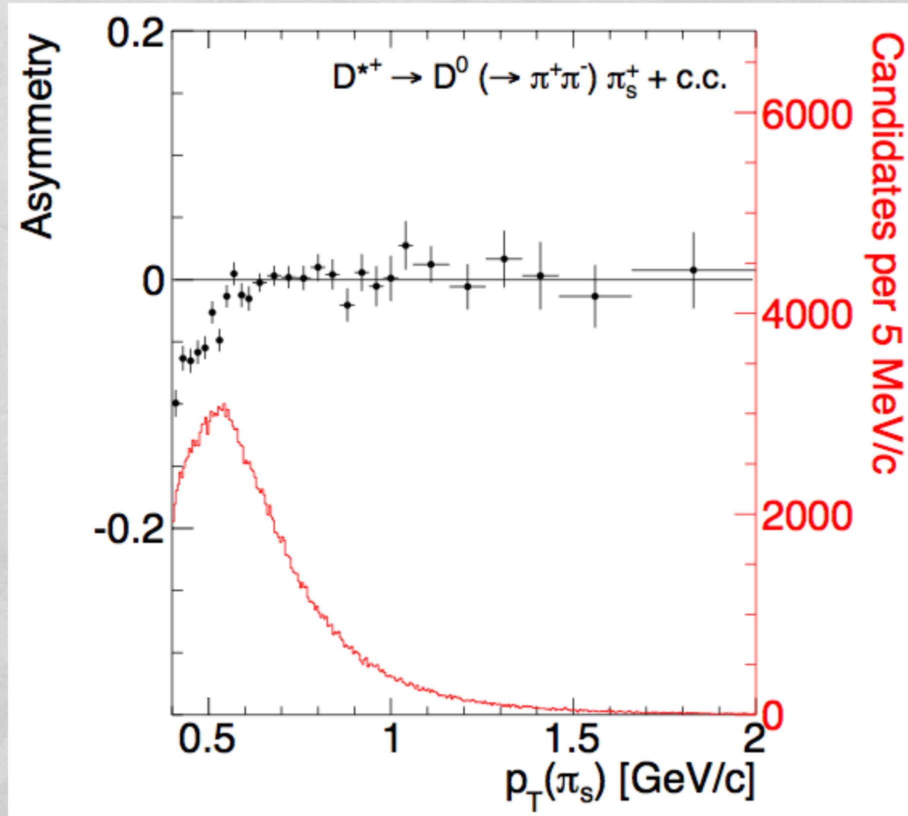
Instrumental asymmetries

D^0 flavor determined through the $D^* \to D^0 \pi_s$ decay, but soft pion induces spurious asymmetries

$A(KK^*) = A_{CP}(K^+K^-) + \delta(\pi_s)$
$A(\pi\pi^*) = A_{CP}(\pi^+\pi^-) + \delta(\pi_s)$

They cancel in the difference:

$\Delta A_{CP} = A(KK^*) - A(\pi\pi^*)$
$= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$

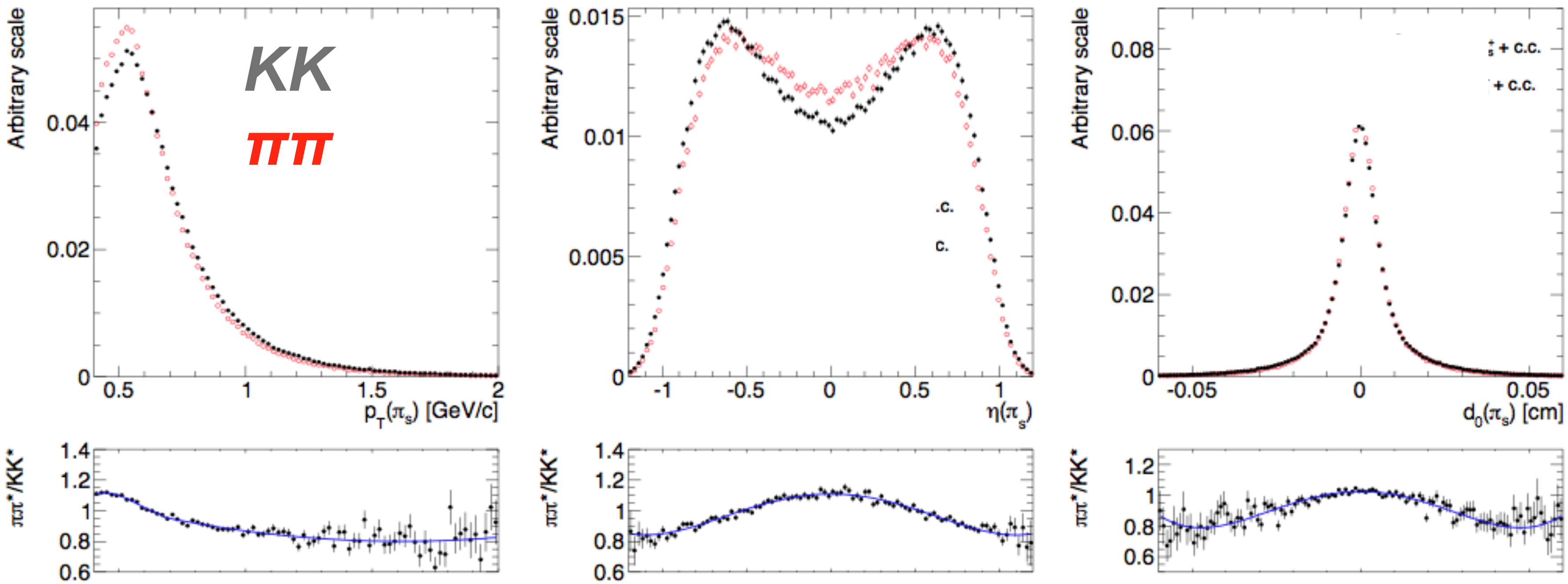


- Additional complication:
  Instrumental asymmetry is pt-dependent: cancellation only works if π_s distributions are the same for KK and $\pi\pi$,
- This is not the case -> need a fix.

Kinematic differences

- In spite of decays being similar, mass differences lead to different KK and ππ kinematic distributions

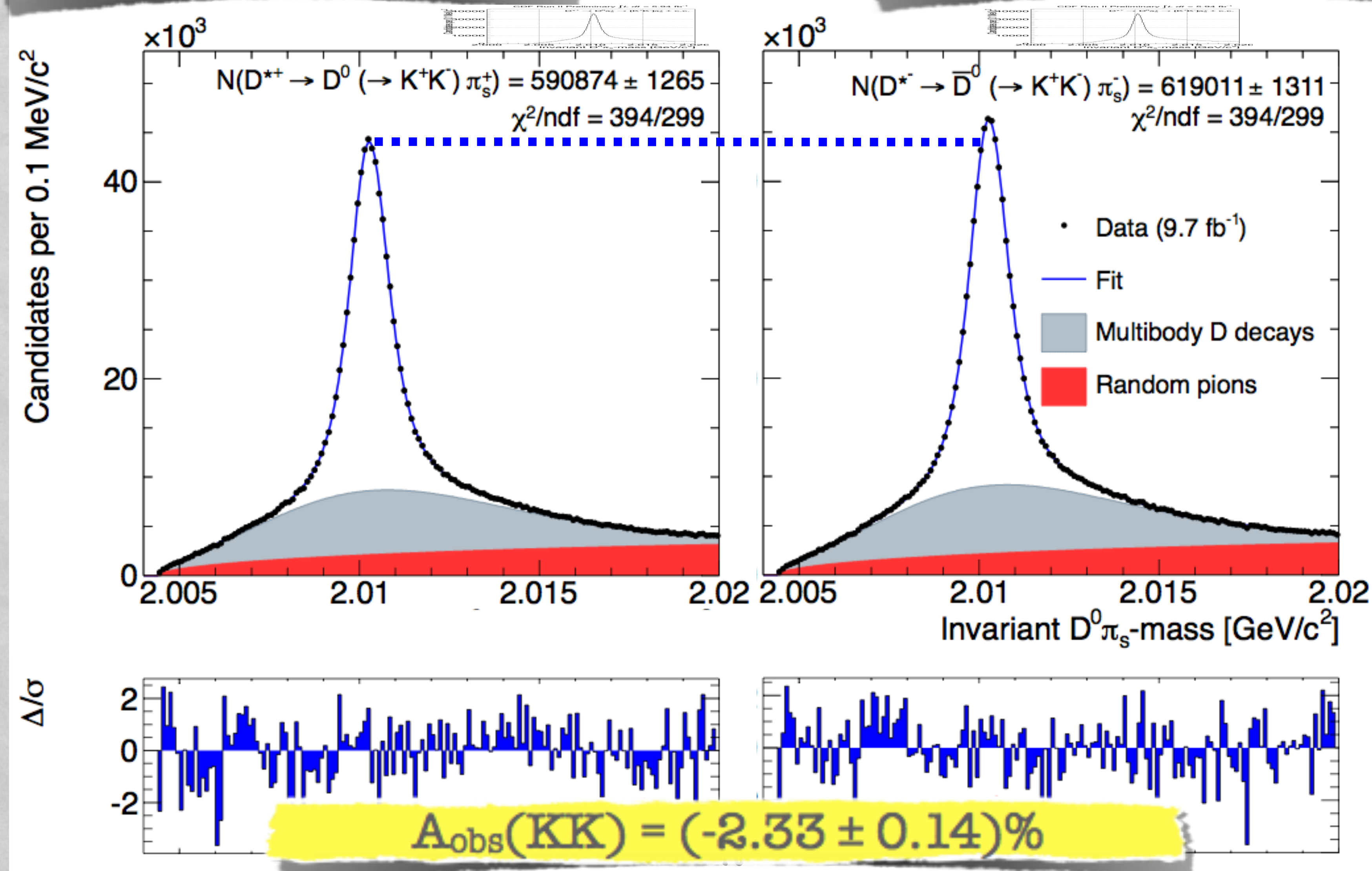
- We reweight distributions to ensure accurate cancellation.



pion transverse momentum *pion pseudorapidity* *pion impact parameter*

$D^0 \to KK$ asymmetry

D^0 (positive pion) $\bar{D}^0$ (negative pion)

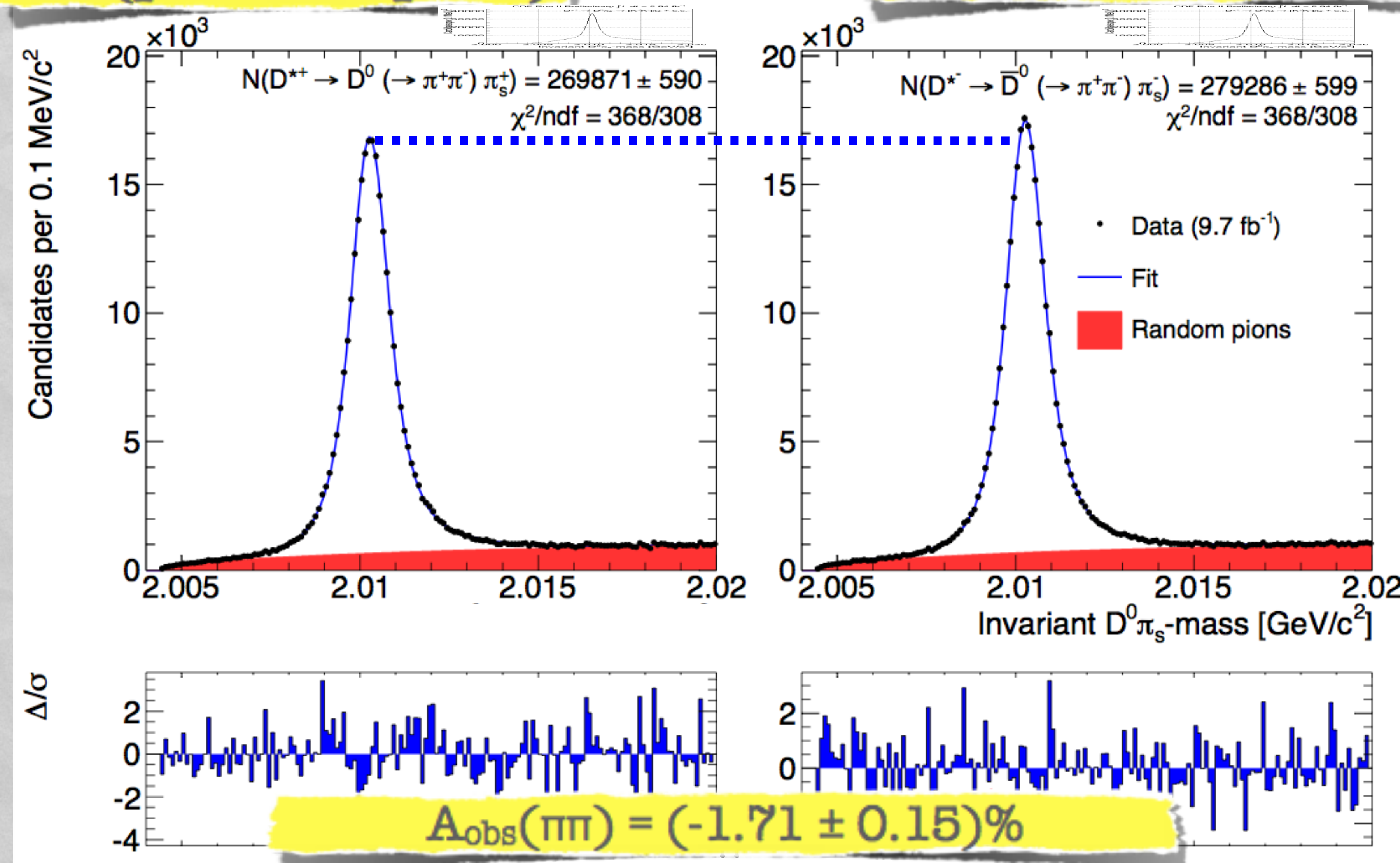


$A_{obs}(KK) = (-2.33 \pm 0.14)\%$

$D^0 \to \pi\pi$ asymmetry

D^0 (positive pion)

$\bar{D}^0$ (negative pion)



$A_{obs}(\pi\pi) = (-1.71 \pm 0.15)\%$

Result

$A_{obs}(KK) - A_{obs}(\pi\pi) = (-2.33 \pm 0.14)\% - (-1.71 \pm 0.15)\% =$

$$\Delta A_{CP} = (-0.62 \pm 0.21\ (stat) \pm 0.10\ (syst))\%$$

CDF Public note 10784

This is 2.7σ away from zero, indicating presence of CP violation in CDF charm data.

The uncertainty of 0.2 % dominated by the sample size.

Systematics and checks

Simulation constrains residual, higher-order instrumental effects

Uncertainties on mass shapes. Residual mismodeling constrained with "anti-tuned" fits.

Shape differences btw + and - D*. Repeat fits with independent models for + and - signals and backgrounds.

Kπ tail leaks into ππ. Effect is the product of the measured Kπ asymmetry (3%) times the size (0.93%) of the contribution

Source	ΔA_{CP} [%]
Approximations in the suppression of detector-induced effects	0.009
Shapes assumed in fits	0.020
Charge-dependent mass distributions	0.100
Asymmetries from residual backgrounds	0.013
Total	0.103

Checks in independent subsamples divided according to kinematic or detector conditions show no anomalies

Consistency checks

Soft pion's direction	ΔA_{CP} (%)
Upward-Forward	-0.37 ± 0.39
Upward-Backward	-1.15 ± 0.40
Downward-Forward	-0.08 ± 0.40
Downward-Backward	-0.89 ± 0.40

$\chi^2/\text{ndf} = 4.4/3$

Data-taking periods	ΔA_{CP} (%)
Pre–July 2008	-0.75 ± 0.28
Post–July 2008	-0.50 ± 0.30

$\chi^2/\text{ndf} = 0.38/1$

Sub-sample	ΔA_{CP} (%)
New candidates only	-0.74 ± 0.27
Old candidates only	-0.46 ± 0.31

$\chi^2/\text{ndf} = 0.46/1$

Comparing with other results

$\Delta A_{CP} = \Delta A_{CP}^{dir} + (\langle \Delta t \rangle / \tau)\, A_{CP}^{ind}$

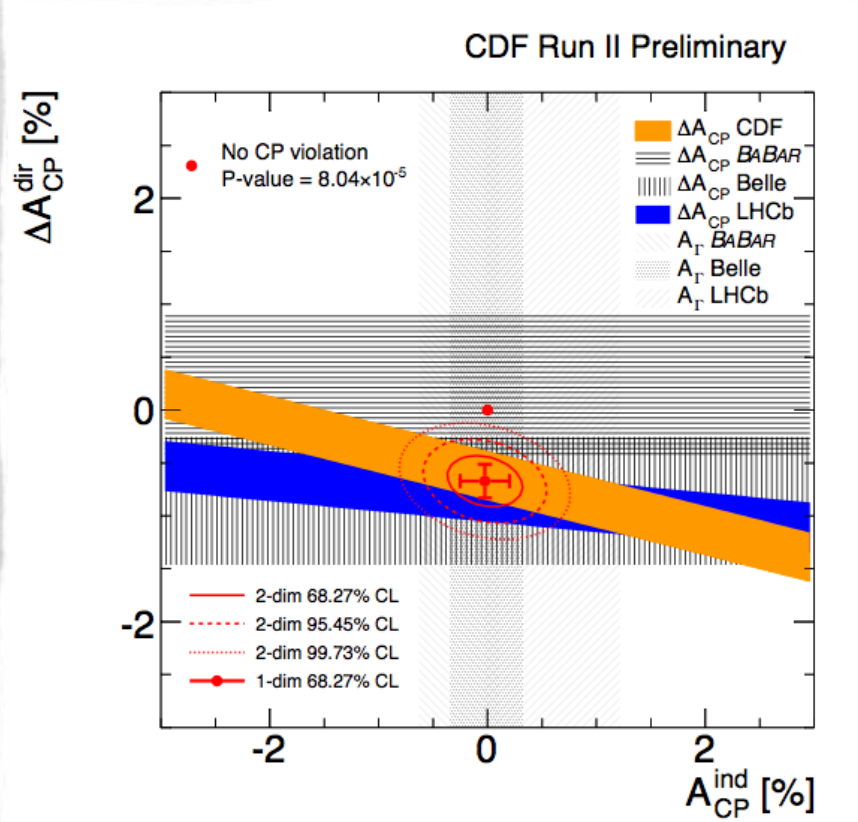
Linear relation between the difference of direct CPV and indirect CPV.

Slope is the difference in average decay-time between observed KK and ππ (experiment-dependent)

Confirm LHCb result within <1σ, and the same resolution.

Combination assuming Gaussian uncertainties and no correlations excludes CP conservation in charm at 3.8σ

HFAG has very similar numbers



$\Delta A_{CP} = (-0.67 \pm 0.16)\%$,
$A_{CP}^{ind} = (-0.02 \pm 0.22)\%$

Measuring Individual A_{CP}'s

- Interestingly, predictions differ on Acp(ππ) vs Acp(KK)

  ⇒ **Measuring the two separately provides more information**

HOW?

- It can be done with the use of 4 samples:
  - D*-tagged $D^0 \to \pi\pi$ $A(\pi\pi^*) = A_{CP}(\pi\pi) + \delta(\pi_s) + A^*$
  - D*-tagged $D^0 \to KK$ $A(KK^*) = A_{CP}(KK) + \delta(\pi_s) + A^*$
  - D*-tagged $D^0 \to K\pi$ $A(K\pi^*) = A_{CP}(K\pi) + \delta(\pi_s) + \delta(K\pi) + A^*$
  - Untagged $D^0 \to K\pi$ $A(K\pi) = A_{CP}(K\pi) + \delta(K\pi) + A0$

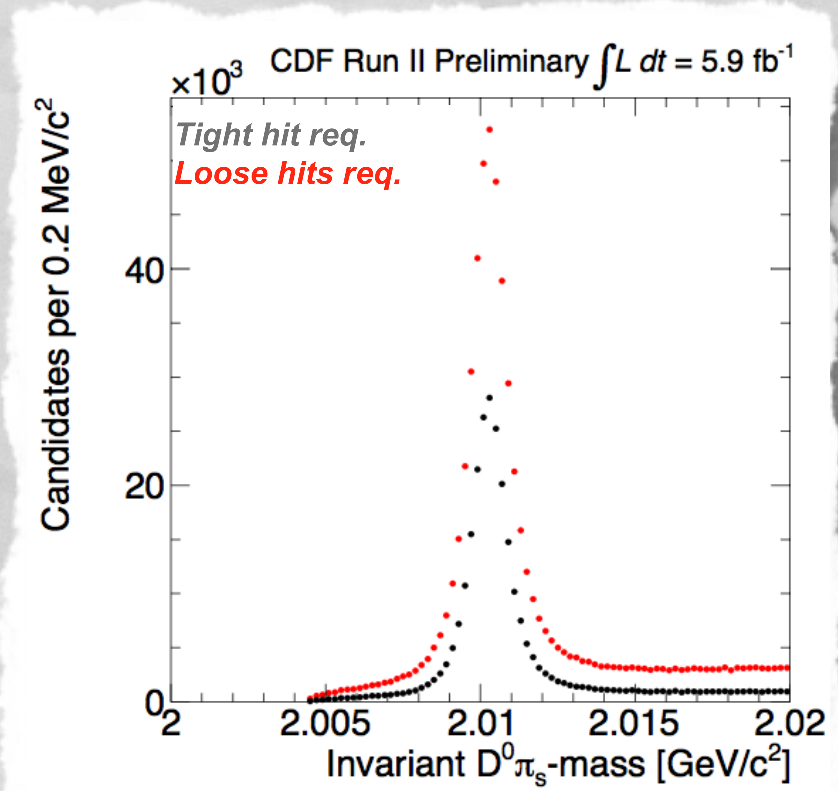
$$\Rightarrow \begin{array}{l} A_{CP}(\pi\pi) = A(\pi\pi^*) - A(K\pi^*) + A(K\pi) - A0 \\ A_{CP}(KK) = A(KK^*) - A(K\pi^*) + A(K\pi) - A0 \end{array}$$

- Works if the production asymmetry of the D^0 is known.
  At CDF it is easy because at p-pbar it is exactly zero !

Tighter quality requirements

Lack of cancellation between channels, and need for an untagged sample requires more care.

- Tigher tracking/selection requirements
- Smaller better understood set of triggers
- Remove D from B decays to avoid possible production bias.
- Complex 4-sample subtraction procedure stress-tested with MC with exaggerated detector effects



Cleaner, but smaller sample. Only performed on first **6fb-1**

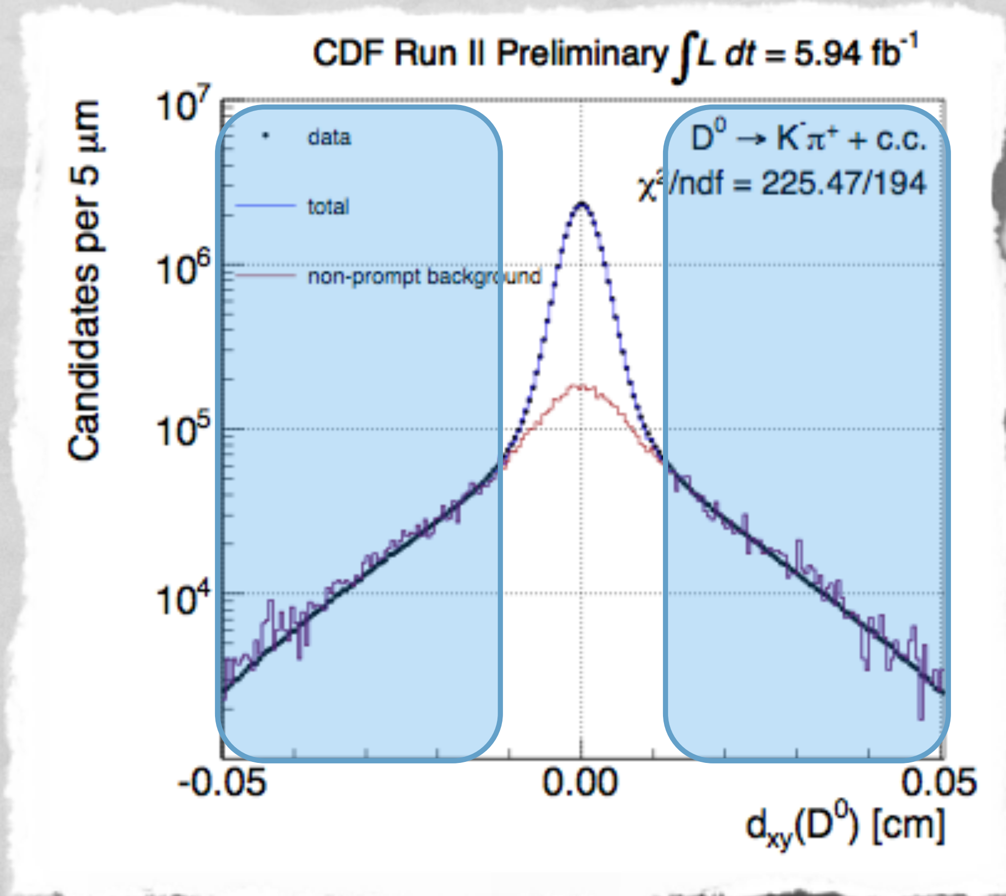
Removal of non-prompt charm

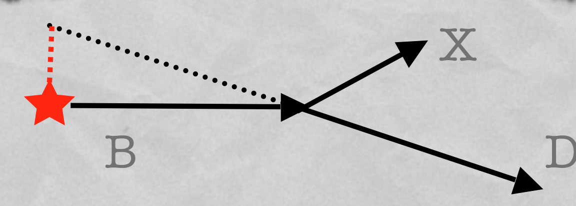
cτ(B) ≈ 450 microns

D from B are 12% of the sample.

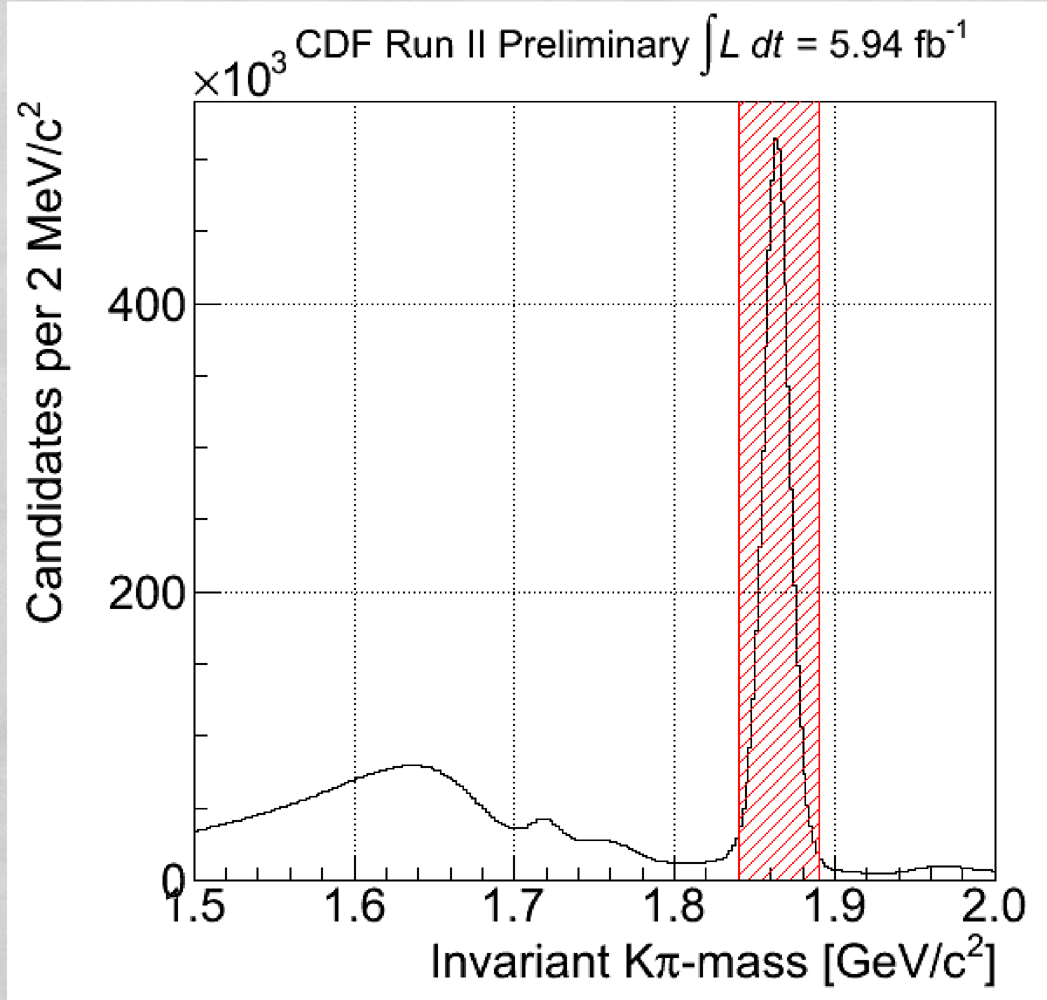
If there's CP violation in the relevant B decay, that would be propagate into the individual asymmetries results.

It cancels in the difference



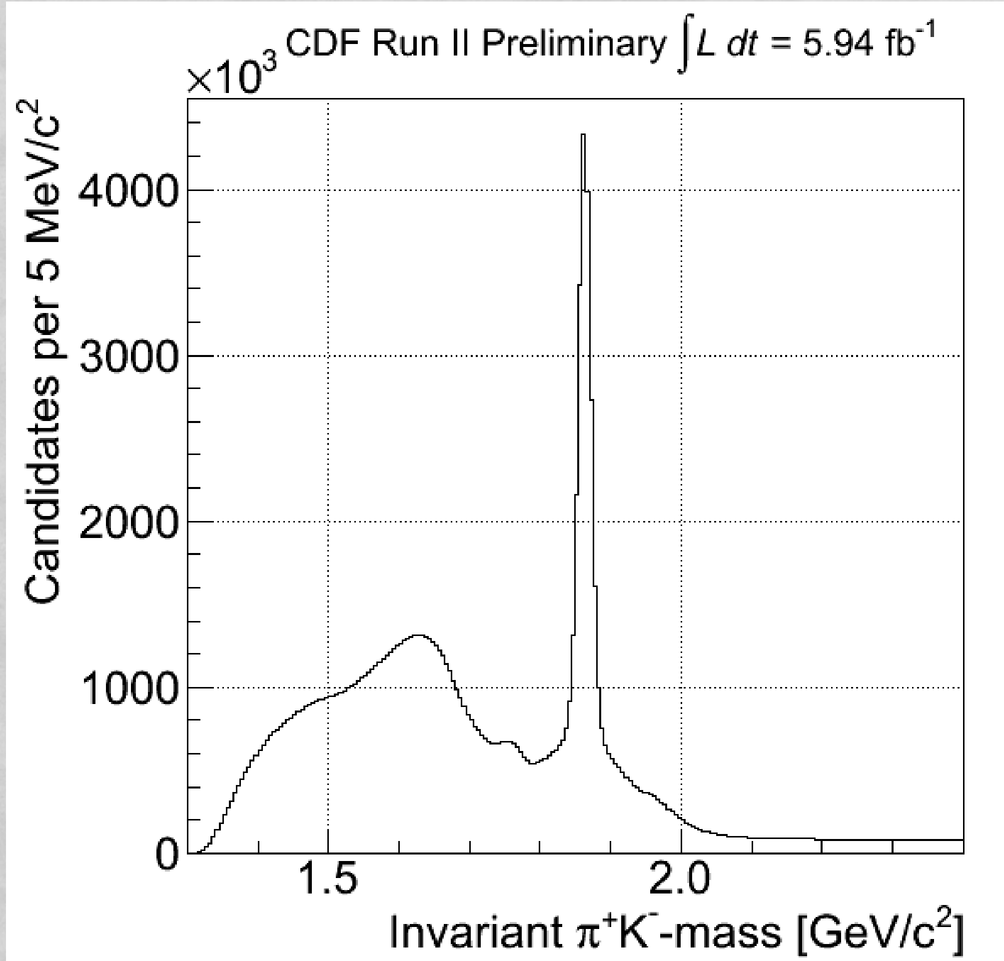


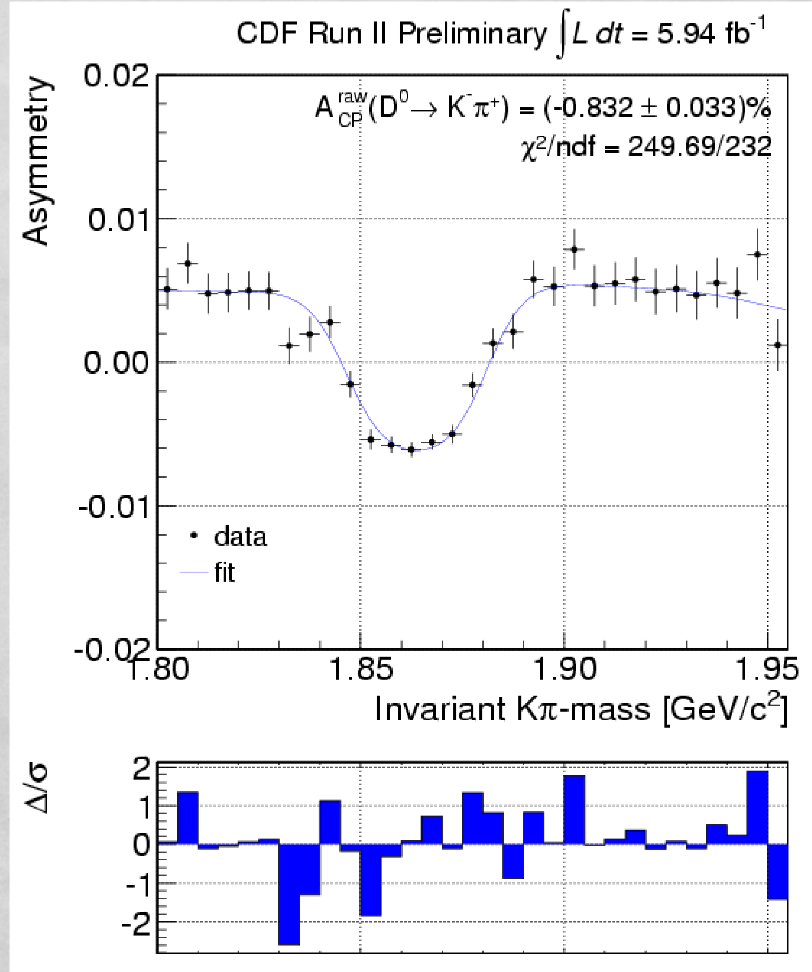
Measuring Individual A_{CP}'s



Tagged Kpi sample: A(Kπ*) = -2.91 ± 0.05 %

Asymmetry of the untagged D^0 sample





Untagged Kpi sample: A(Kπ) = -0.832 ±0.033 %

Results

$A_{CP}(D\text{->}KK) = (-0.24 \pm 0.22 \pm 0.09)\%$

$A_{CP}(D\text{->}\pi\pi) = (+0.22 \pm 0.24 \pm 0.11)\%$

PRD 85, 012009 (2012)

•World's most precise measurements

•Seem to indicate equal and opposite effects, as predicted by some

•They are much more sensitive to A_{cp}^{ind} than the difference. **Assuming** A_{cp}^{dir} are indeed opposite, would yield a bound on A_{cp}^{ind}

$$A(KK)+A(\pi\pi) = 2\langle t\rangle/\tau\, A_{CP}^{ind} \approx 5\, A_{CP}^{ind}$$

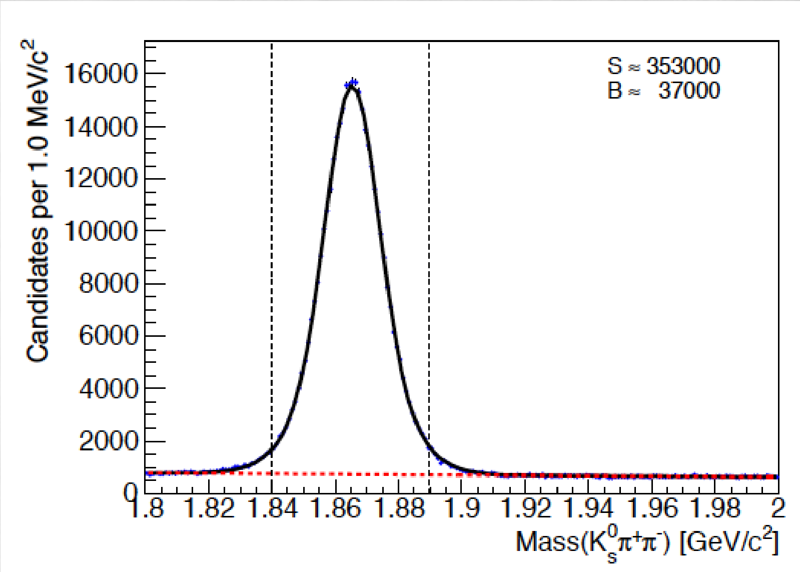
$$A_{CP}^{ind} = -0.01 \pm 0.06 \pm 0.04\ \%$$

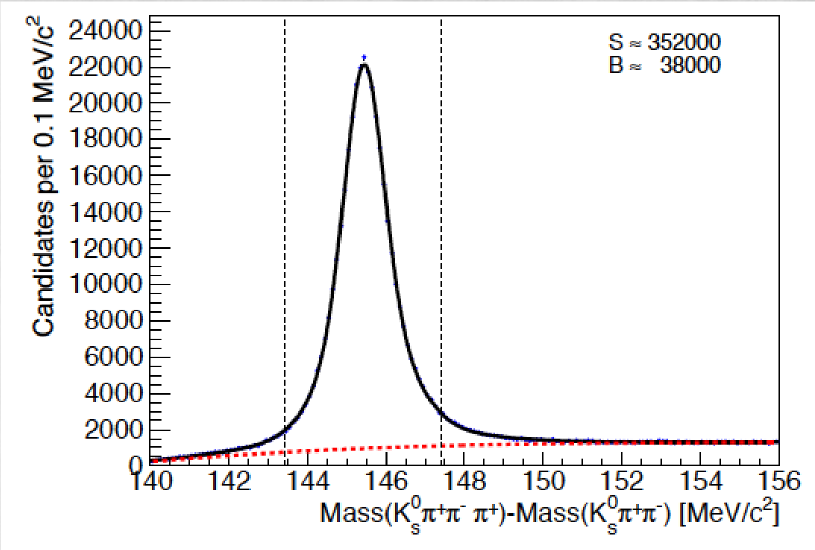
•This could in principle be improved by performing time-dependent analysis and/or going to larger sample.

CPV in $D^0 \to K_s \pi\pi$

$D^0 \to K_s\pi\pi$ sample

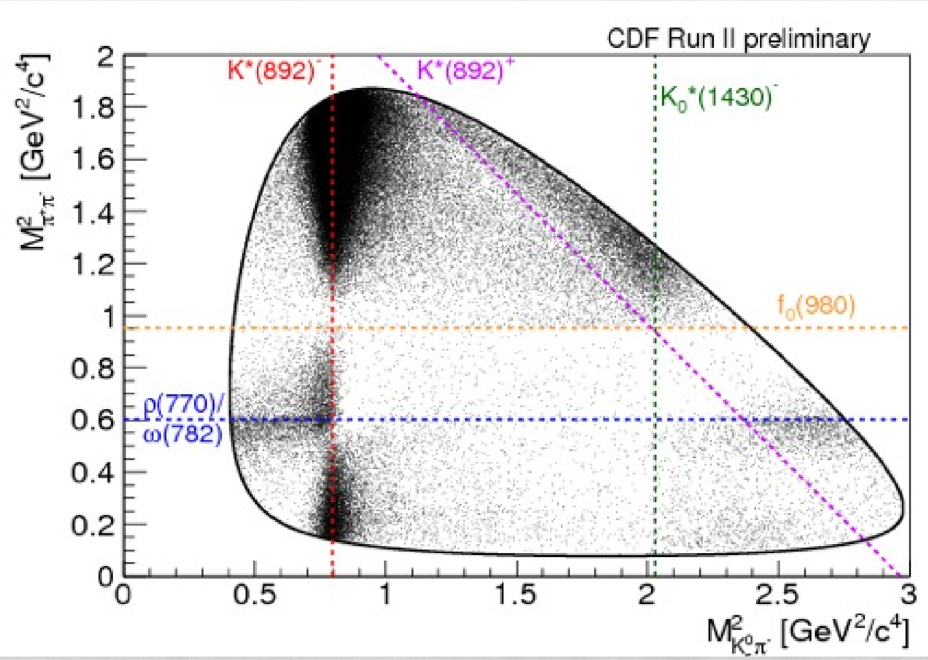
- Reconstruct via the same i.p. trigger as D->hh (trigger on pions, not K_s)
- Require displaced vertex +NN selection
- ~350,000 D*-tagged candidates in $6fb^{-1}$
- Background <10%





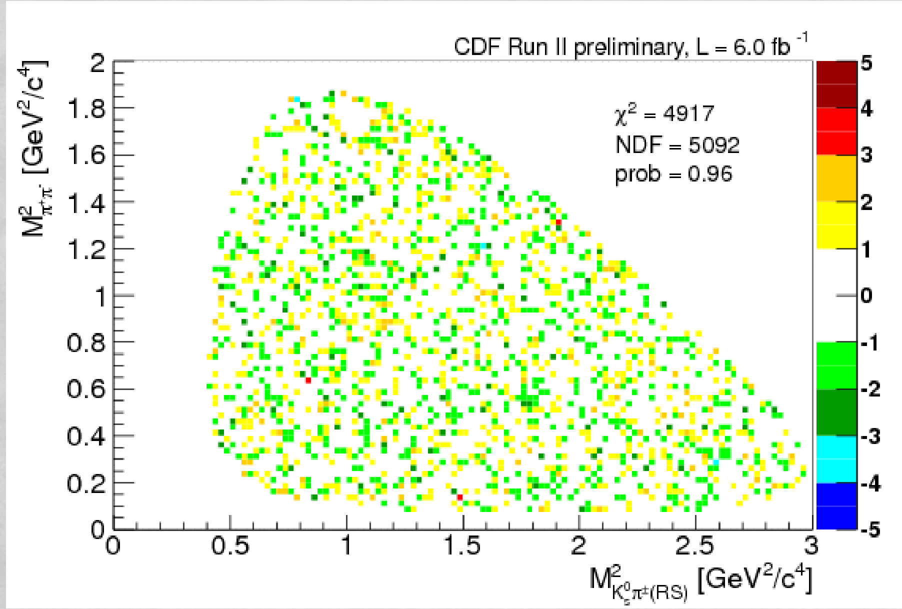
$D^0 \rightarrow K_s\pi\pi$ Dalitz plot

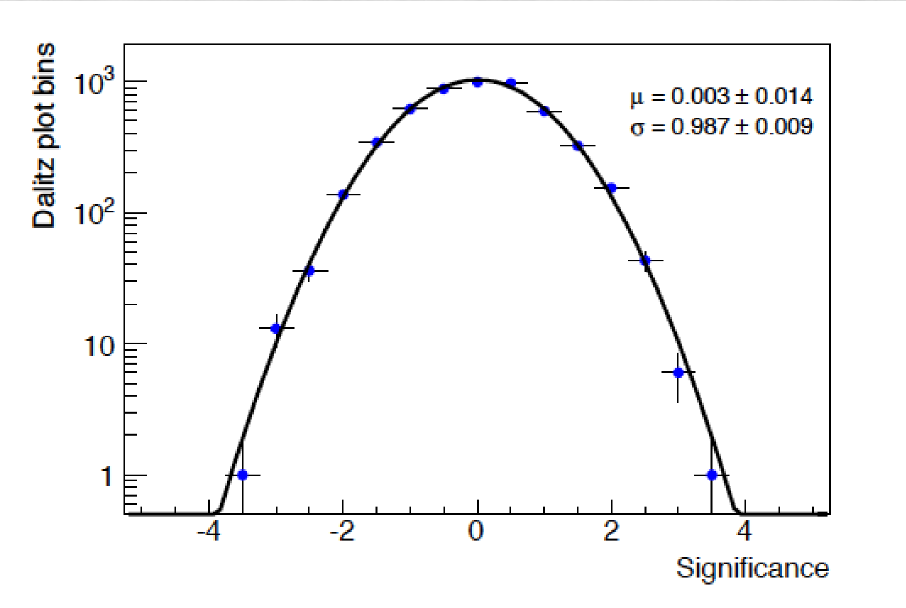
- Look for CPV in the resonant structures of D*-tagged D^0 decaying to $K_s\pi+\pi-$.
- 2 methods:
    - Bin-by-bin
    - Fit the population of each subresonance and compare D^0 and anti-D^0.



- As done for D->hh, the distributions of D* pions are equalized by reweighting before calculating asymmetries, to ensure cancellation of instrumental biases.

$D^0 \to K_s\pi\pi$ asymmetry function





- Bin-by-bin asymmetry significance (units of sigma)
- Shows no significant effect over the Dalitz plot

$D^0 \to K_s\pi\pi$ resonance fit

- Simultaneous fit, isobar model.

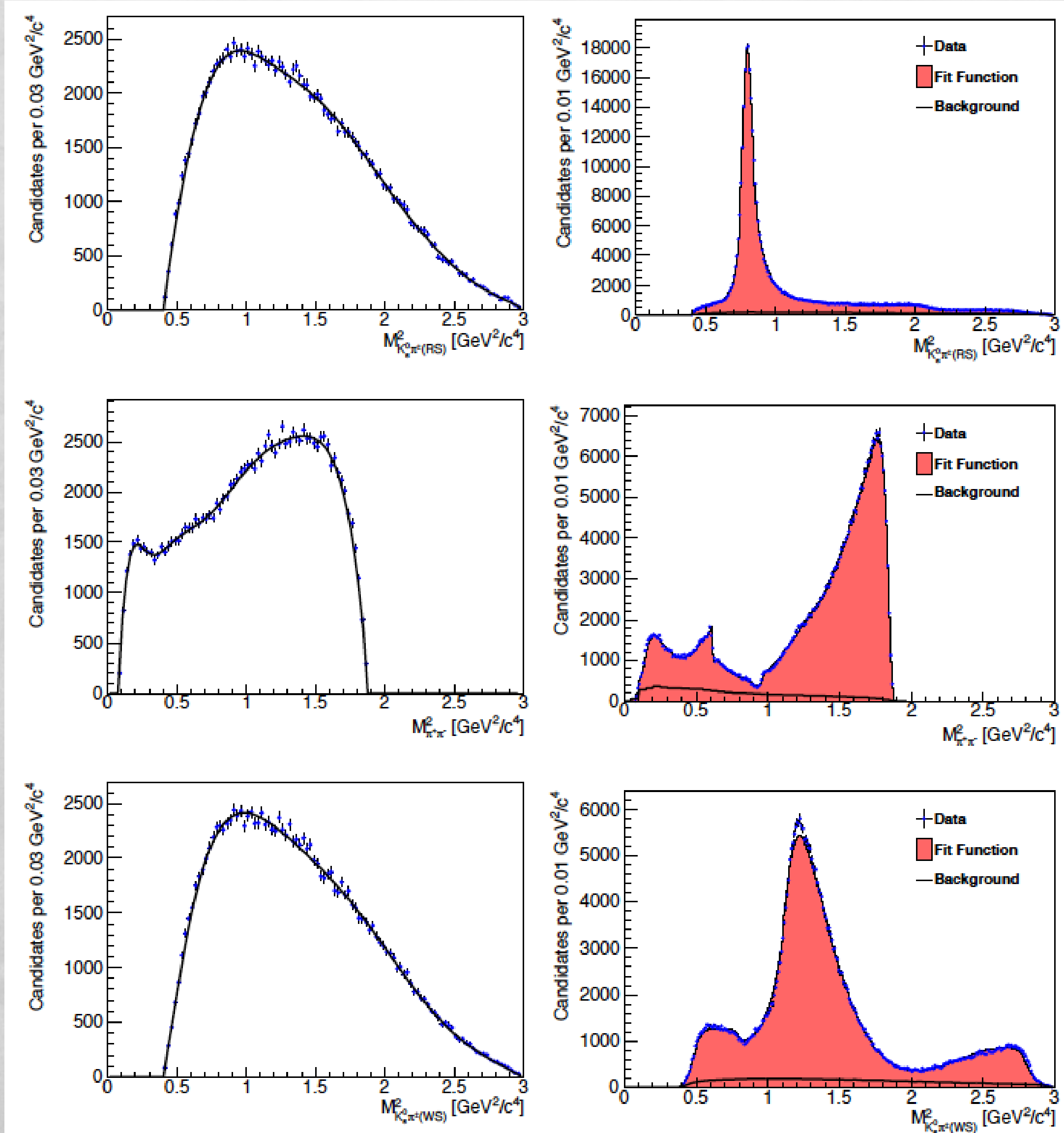
- Fit includes acceptance variations over the Dalitz space, evaluated by detailed trigger and detector simulation

- Again, kinematic differences effects between D*+ and D*- are eliminated by reweighting

- D^0 sideband-subtraction of background

- Obtain very good fit - minor mismatches have negligible impact on A_{CP}

- First time in hadron collisions



Simulated PS Data fit

$D^0 \to K_s \pi\pi$ resonance fit

•Significantly improved precision with respect to previous results [CLEO, PRD70, 091101 (2004)]

Resonance	$\mathcal{A}_{\text{FF}}$ (CDF) [%]	$\mathcal{A}_{\text{FF}}$ (CLEO) [%]
$K^*(892)^-$	$0.36 \pm 0.33 \pm 0.40$	$2.5 \pm 1.9\,^{+1.5}_{-0.7}\,^{+2.9}_{-0.3}$
$K_0^*(1430)^-$	$3.96 \pm 2.41 \pm 3.77$	$-0.2 \pm 11.3\,^{+8.6}_{-4.9}\,^{+1.9}_{-1.0}$
$K_2^*(1430)^-$	$2.86 \pm 3.97 \pm 4.07$	$-7 \pm 25\,^{+8}_{-26}\,^{+10}_{-1}$
$K^*(1410)^-$	$-2.32 \pm 5.69 \pm 6.39$	$\cdots$
$\rho(770)$	$-0.05 \pm 0.50 \pm 0.08$	$3.1 \pm 3.8\,^{+2.7}_{-1.8}\,^{+0.4}_{-1.2}$
$\omega(782)$	$-12.56 \pm 6.01 \pm 2.59$	$-26 \pm 24\,^{+22}_{-2}\,^{+2}_{-4}$
$f_0(980)$	$-0.40 \pm 2.18 \pm 1.63$	$-4.7 \pm 11.0\,^{+24.9}_{-7.4}\,^{+0.3}_{-4.8}$
$f_2(1270)$	$-3.95 \pm 3.35 \pm 3.04$	$34 \pm 51\,^{+25}_{-71}\,^{+21}_{-34}$
$f_0(1370)$	$-0.49 \pm 4.61 \pm 7.65$	$18 \pm 10\,^{+2}_{-21}\,^{+13}_{-6}$
$\rho(1450)$	$-4.11 \pm 5.21 \pm 8.11$	$\cdots$
$f_0(600)$	$-2.65 \pm 2.73 \pm 3.61$	$\cdots$
σ_2	$-6.80 \pm 7.63 \pm 3.75$	$\cdots$
$K^*(892)^+$	$1.03 \pm 5.66 \pm 2.06$	$-21 \pm 42\,^{+17}_{-28}\,^{+22}_{-4}$
$K_0^*(1430)^+$	$12.21 \pm 11.22 \pm 10.29$	$\cdots$
$K_2^*(1430)^+$	$-9.74 \pm 13.53 \pm 29.14$	$\cdots$
$K^*(1680)^-$	$\cdots$	$-36 \pm 19\,^{+9}_{-35}\,^{+5}_{-1}$

$D^0 \to K_s \pi\pi$

$$\mathcal{M} = a_0 \cdot e^{i\delta_0} + \sum_j a_j \cdot e^{i(\delta_j + \phi_j)} \cdot (1 + \frac{b_j}{a_j}) \cdot \mathcal{A}_j \,,$$

$$\overline{\mathcal{M}} = a_0 \cdot e^{i\delta_0} + \sum_j a_j \cdot e^{i(\delta_j - \phi_j)} \cdot (1 - \frac{b_j}{a_j}) \cdot \mathcal{A}_j \,.$$

Channel by channel CPV components and phase

Conclusion: **No evidence for CPV in any mode**

Resonance	b	ϕ [°]
$K^*(892)^-$	$0.004 \pm 0.004 \pm 0.011$	$-0.8 \pm 1.4 \pm 1.3$
$K_0^*(1430)^-$	$0.044 \pm 0.028 \pm 0.041$	$-1.8 \pm 1.7 \pm 2.2$
$K_2^*(1430)^-$	$0.018 \pm 0.024 \pm 0.023$	$-1.1 \pm 1.8 \pm 1.1$
$K^*(1410)^-$	$-0.010 \pm 0.037 \pm 0.021$	$-1.6 \pm 1.9 \pm 2.2$
$\rho(770)$	$-0.003 \pm 0.006 \pm 0.008$	$-0.5 \pm 1.5 \pm 1.4$
$\omega(782)$	$-0.003 \pm 0.002 \pm 0.000$	$-1.8 \pm 2.2 \pm 1.4$
$f_0(980)$	$-0.001 \pm 0.005 \pm 0.004$	$-0.1 \pm 1.3 \pm 1.1$
$f_2(1270)$	$-0.035 \pm 0.037 \pm 0.013$	$-2.0 \pm 1.9 \pm 2.1$
$f_0(1370)$	$-0.002 \pm 0.008 \pm 0.021$	$-0.1 \pm 1.7 \pm 2.8$
$\rho(1450)$	$-0.016 \pm 0.022 \pm 0.135$	$-1.7 \pm 1.7 \pm 3.9$
$f_0(600)$	$-0.012 \pm 0.017 \pm 0.025$	$-0.3 \pm 1.5 \pm 1.4$
σ_2	$-0.011 \pm 0.012 \pm 0.004$	$-0.2 \pm 2.9 \pm 1.1$
$K^*(892)^+$	$0.001 \pm 0.005 \pm 0.002$	$-3.8 \pm 2.3 \pm 1.2$
$K_0^*(1430)^+$	$0.022 \pm 0.024 \pm 0.035$	$-3.3 \pm 4.0 \pm 3.9$
$K_2^*(1430)^+$	$-0.018 \pm 0.029 \pm 0.017$	$4.2 \pm 5.3 \pm 3.0$

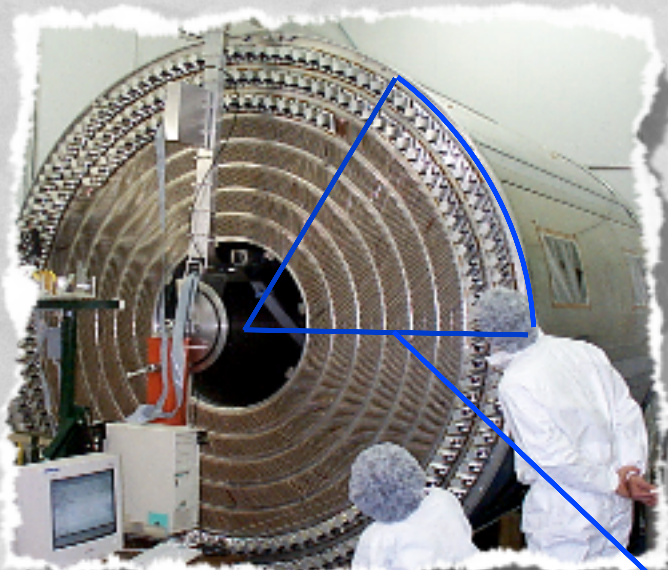
Integrated asymmetry A_{CP} = (- 0.05 +- 0.57 +- 0.54)%

Summary

- Currently CDF has the most precise measurements of ΔA_{CP}, $A_{CP}(\pi\pi, KK)$, and $A_{CP}(K_s\pi\pi)$
- Measurement of CPV in $D \rightarrow hh$ using whole CDF dataset finds *strong indication of CPV*, in agreement with similar results from LHCb, and motivates further exploration. No CPV detected in $K_s\pi\pi$
- $A_{CP}(D \rightarrow hh)$ still somewhat improvable, and more measurements in other channels conceivable - especially useful the unique lack of production asymmetry at CDF.
- CDF is looking at keeping its capability to do analysis for a few more years, to perform further investigations.

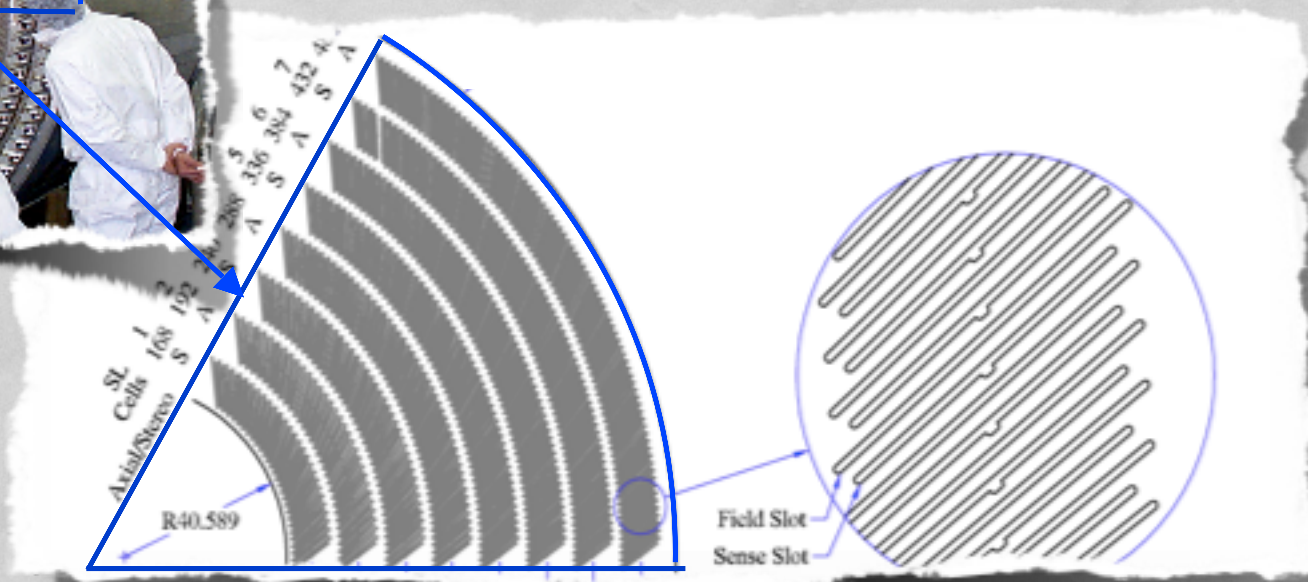
Backup

CDF tracker non-symmetric structure



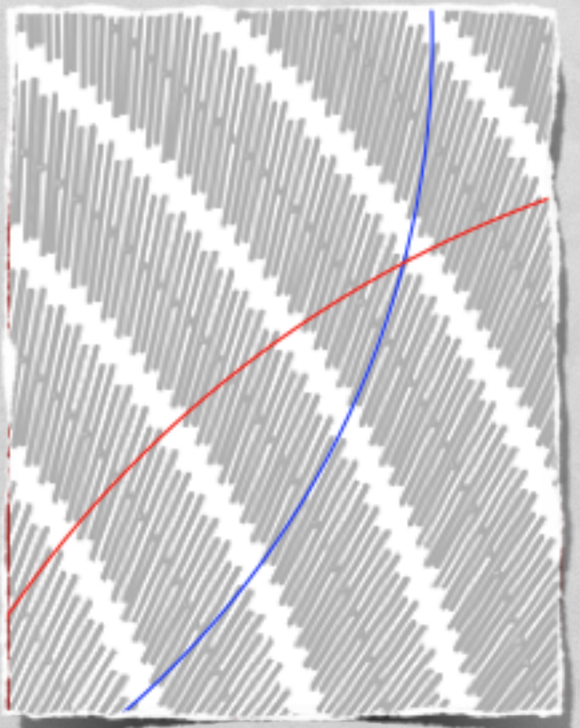
Large radius drift chamber.

Cells tilt of 35° wrt radial direction

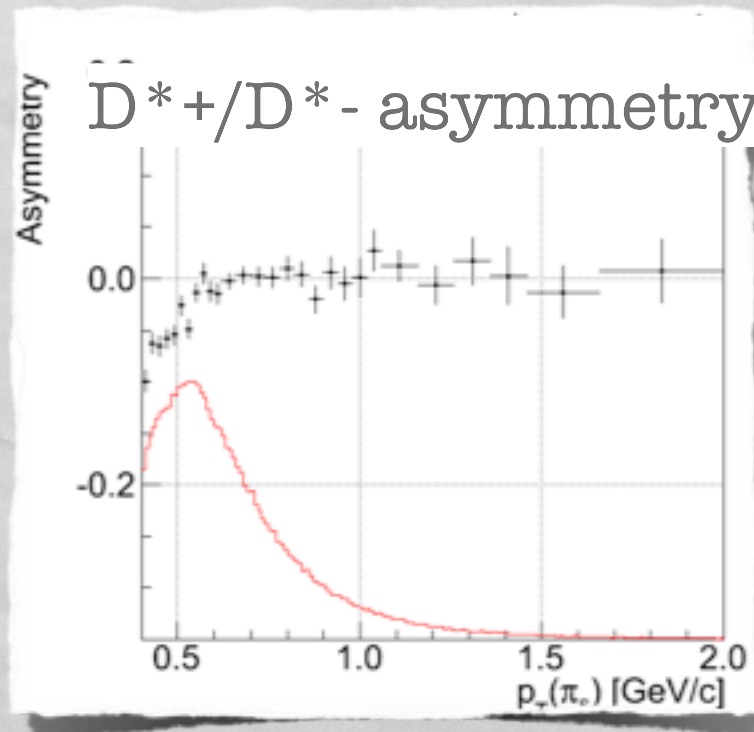


Instrumental asymmetry

•D* tag comes with a price: it introduces instrumental asymmetry in pion detection - cancels out in the difference



+ and - particles hit cells at different angles. Impacts track efficiency, which becomes charge/momentum dependent.



Individual asymmetries

$D^\star \to D^0\pi_s \to [KK]\pi_s$ $\quad A\ (KK^\star) = A_{CP}(KK) + \delta(\pi_s)$

cancel asymmetry due to π_s^+/π_s^-
different reconstruction efficiencies

$D^\star \to D^0\pi_s \to [K\pi]\,\pi_s$ $\quad A\ (K\pi^\star) = A_{CP}(K\pi) + \delta(\pi_s) + \delta(K\pi)$

cancel asymmetry due to K^+/K^-
different interaction with matter

$+$

possible CPV
in $D^0 \to K\pi$

$D^0 \to [K\pi]$ $\quad A\ (K\pi) = A_{CP}(K\pi) + \delta(K\pi)$

The physical A_{CP} could be extracted through the combination:

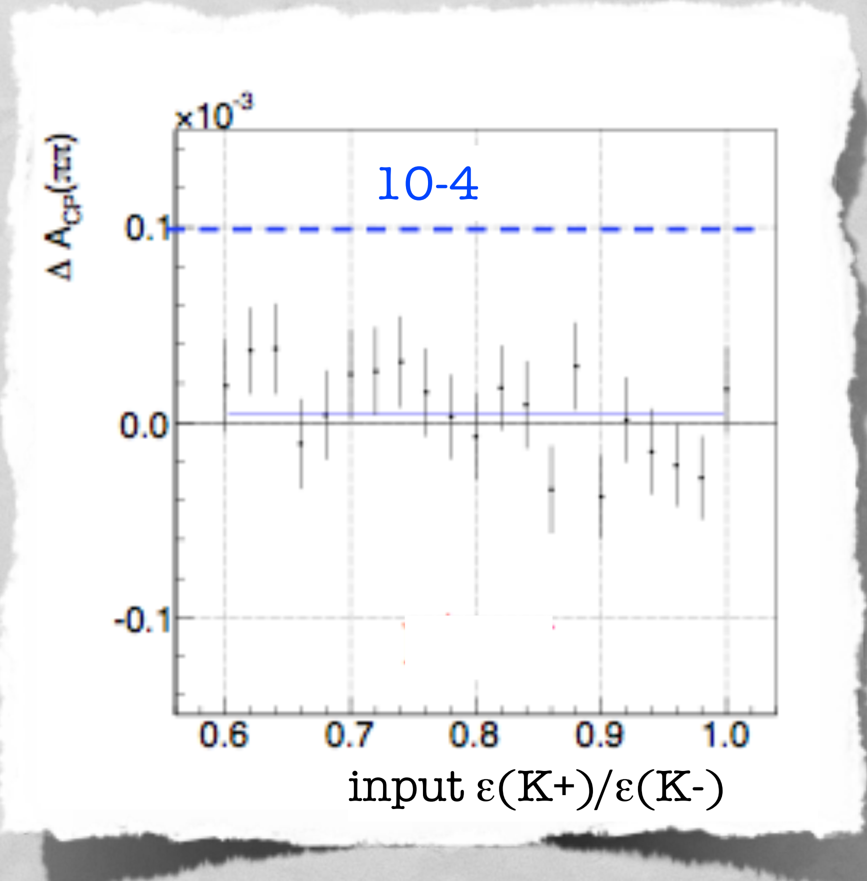
$$A_{CP}(KK) = A(KK^*) - A\ (K\pi^*) + A(K\pi)$$

Higher order effetcs

Measurement repeated on many simulated samples.

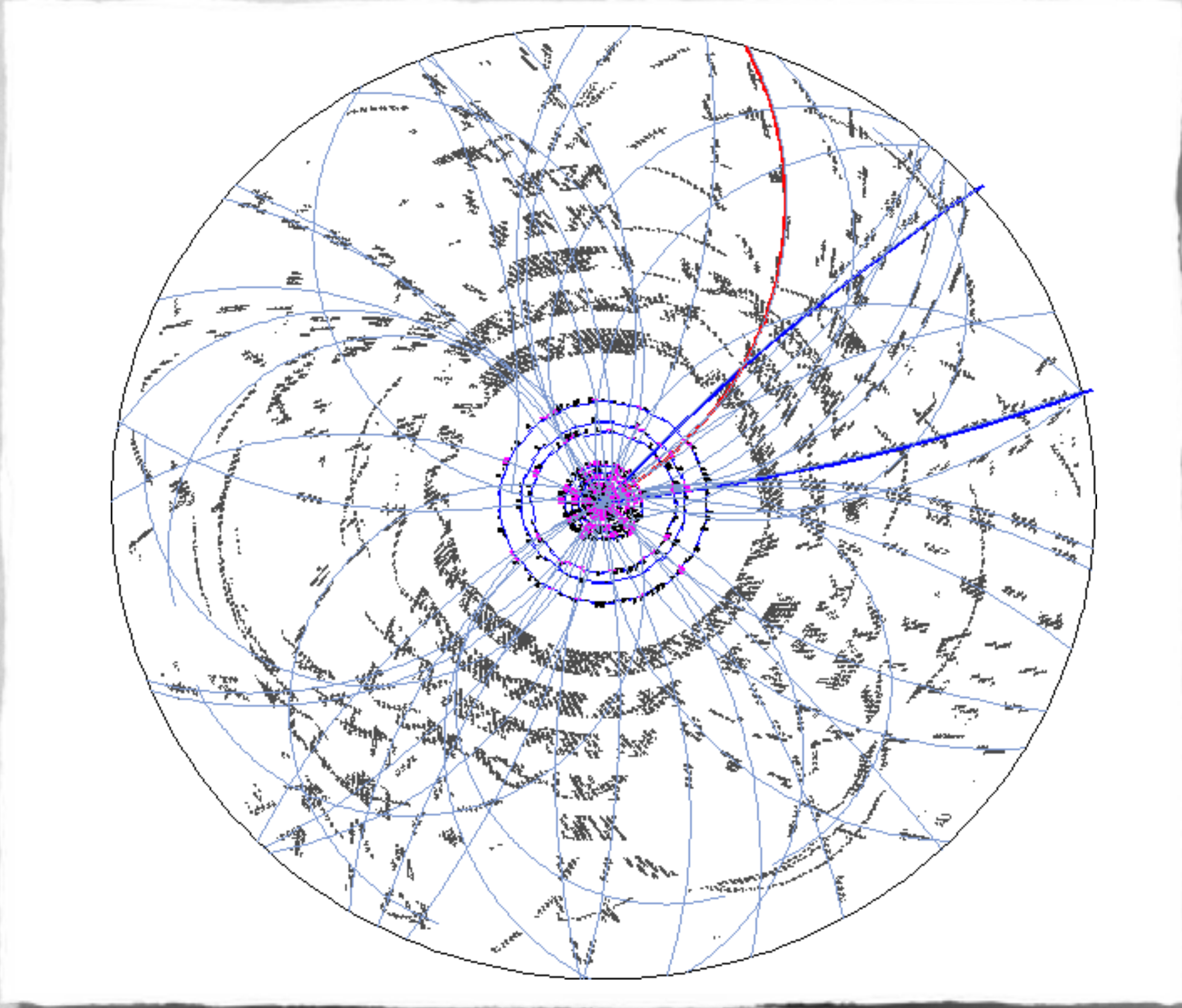
Known and different instrumental asymmetries are injected as functions of kinematics.

Larger effect seen quoted as systematic uncertainty



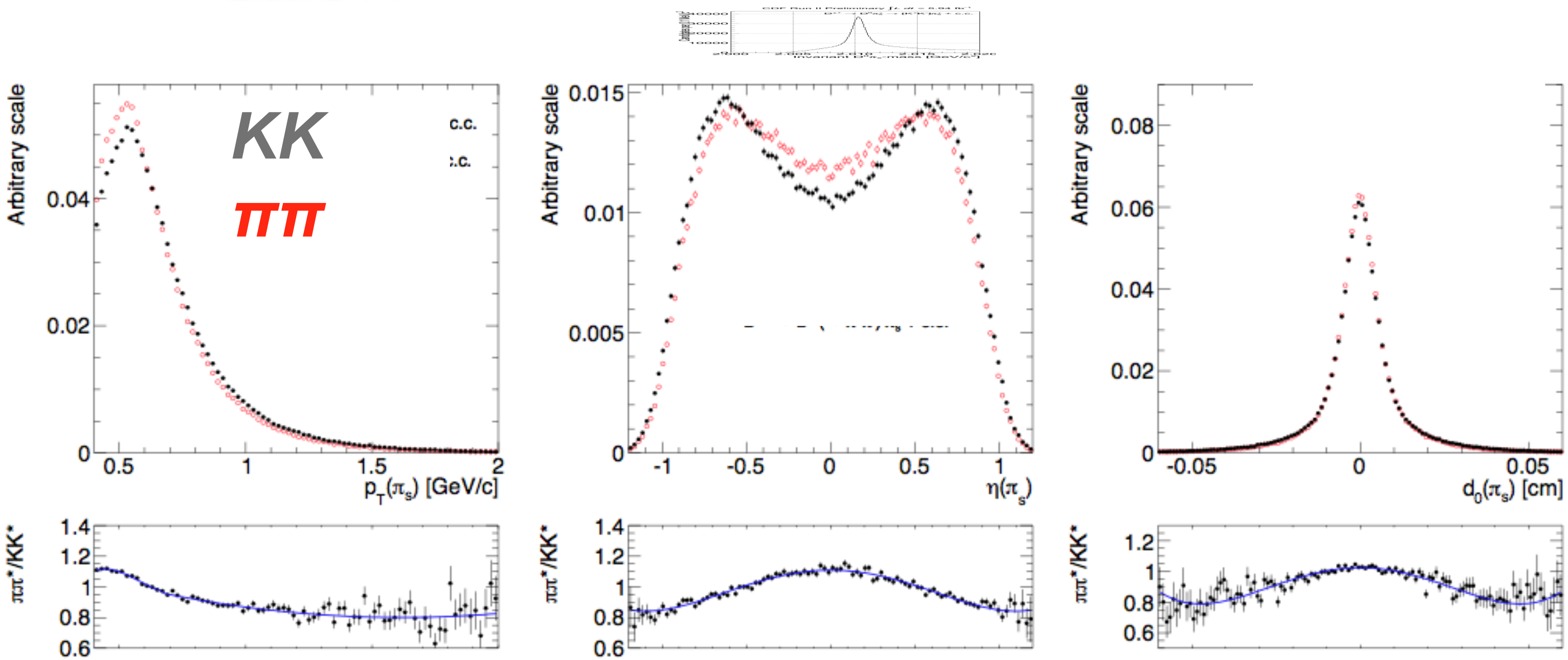
Different relative efficiencies for detecting + vs - kaons

Hello, charming..



Kinematics differences

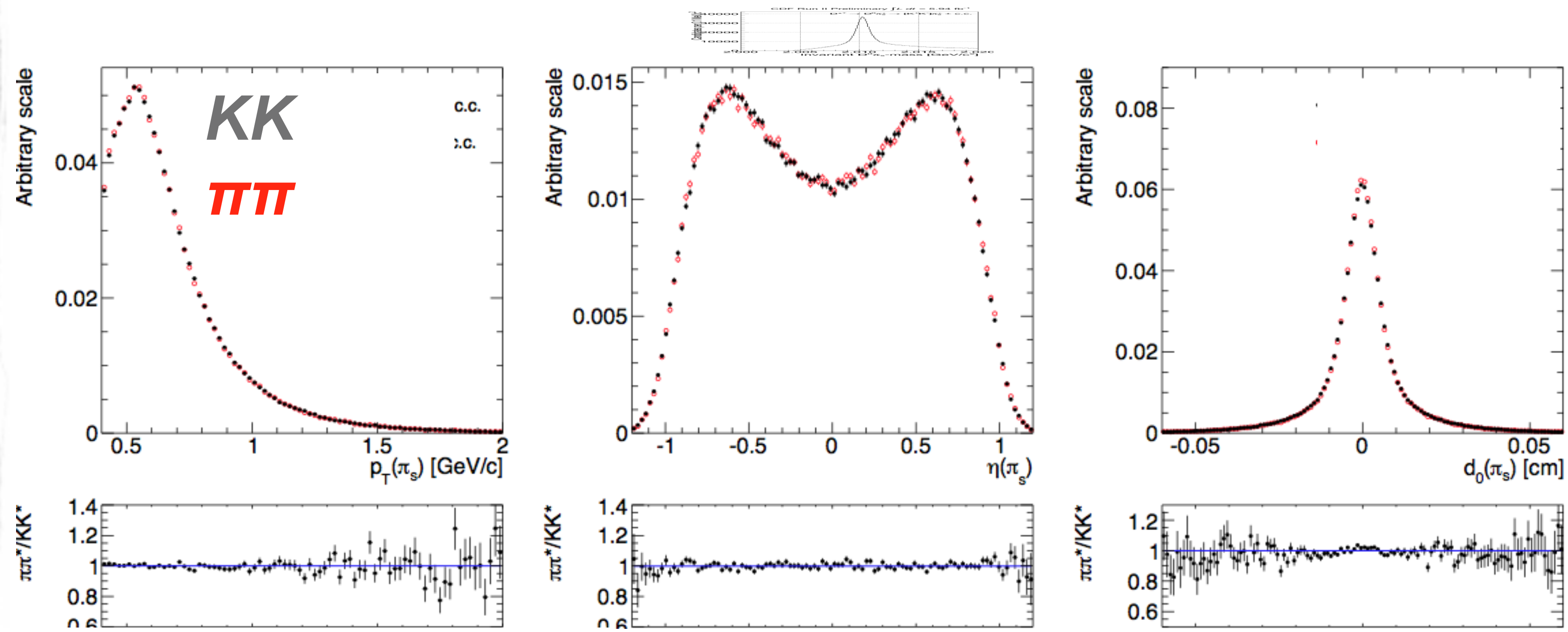
Instrumental effects depend on kinematics. Need to reweight KK and ππ kinematics for realizing cancellation



pion transverse momentum *pion pseudorapidity* *pion impact parameter*

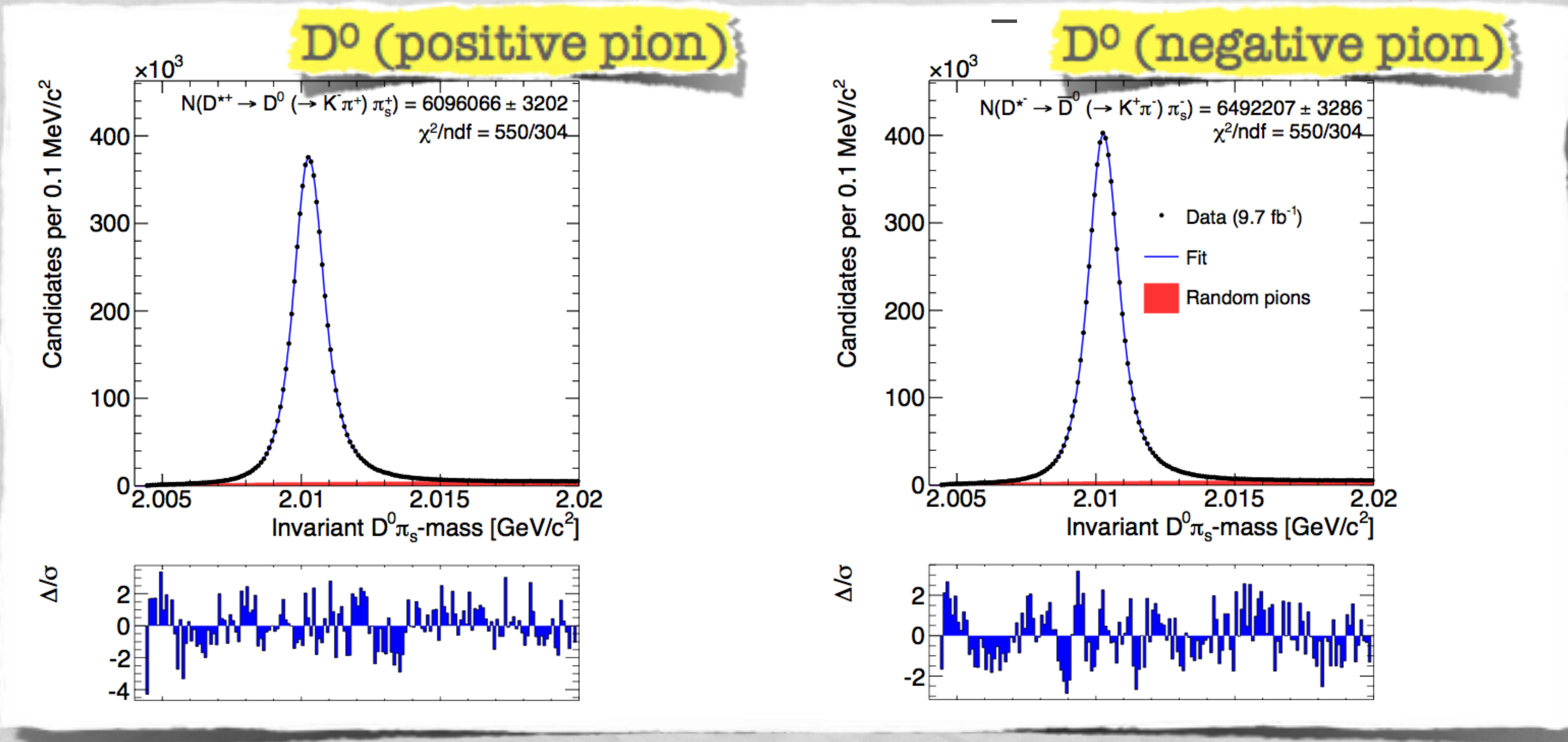
Reweighting

Reweight events so that kinematic distributions become equal



pion transverse momentum *pion pseudorapidity* *pion impact parameter*

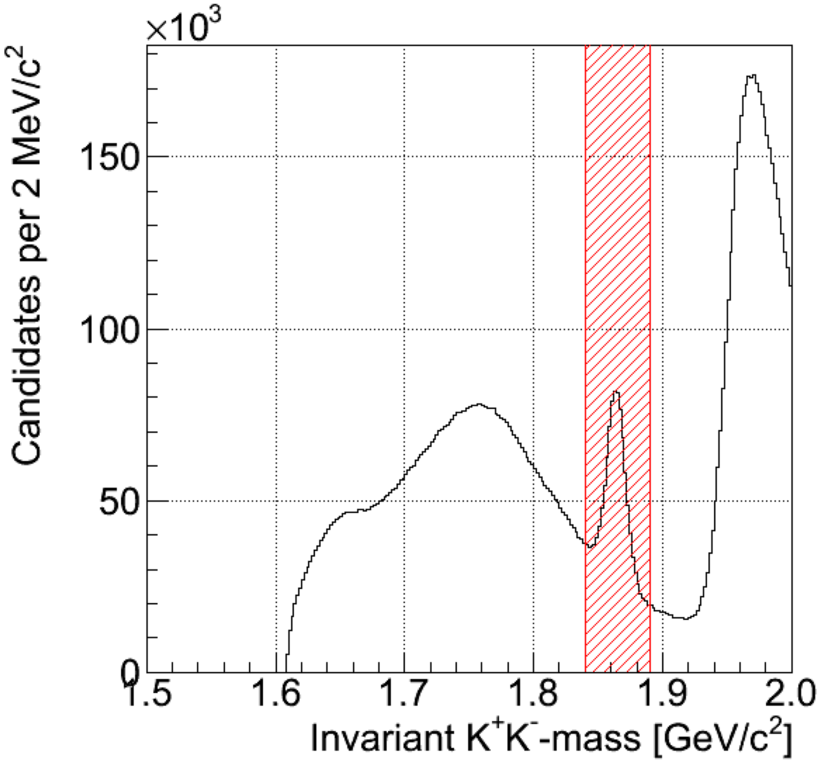
Getting the D* mass shapes

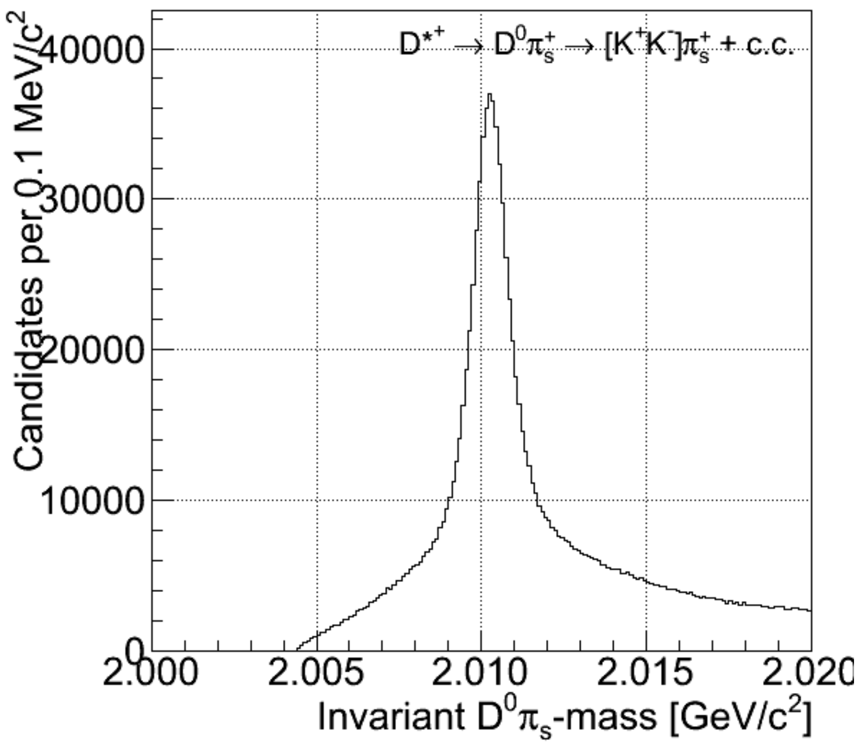


Signal: functional form from simulation. Tune parameters in 12.5M D0->Kπ decays (10x more abundant wrt KK and ππ)

Random pion: combine real D0 with all π from subsequent events in data.

Cut on KK mass and fit D* mass



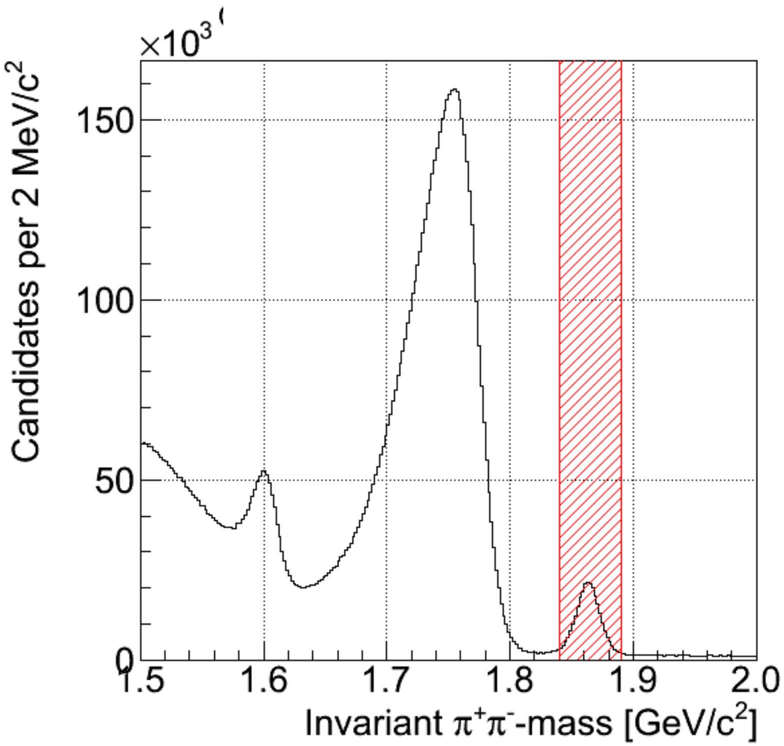


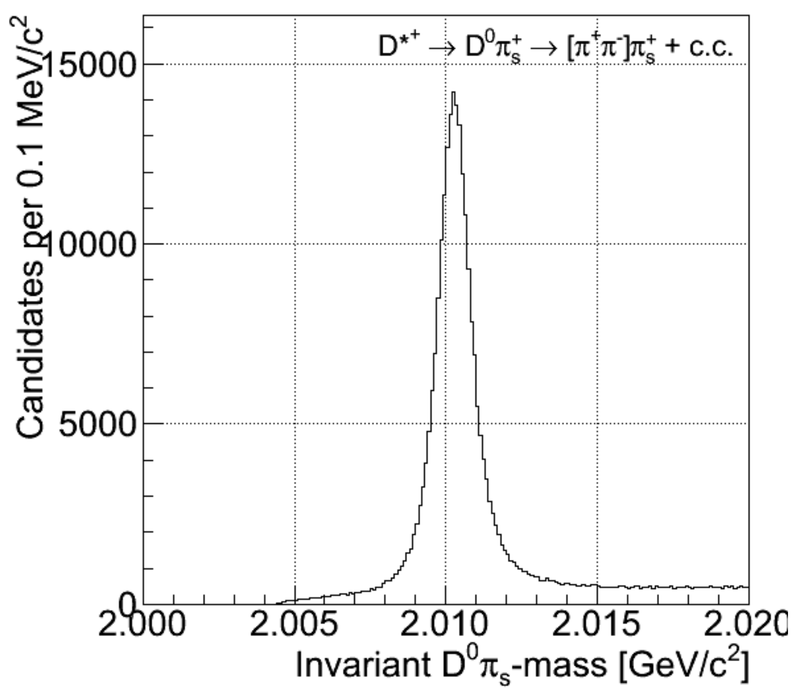
1. Cut on D^0 mass

2. Attach soft pion

3. Fit in D* mass

Cut on ππ mass and fit D* mass





1. Cut on D^0 mass

2. Attach soft pion

3. Fit in D* mass